TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2018, Vol. 18, No. 4, 21-30

Complex Driver Movement Mathematical Model of the Tractive Rolling Stock

Valery Dmitrienko, Alexander Zakovorotniy, Valentin Noskov, Nikolai Mezentsev, Dmitriy Glavchev, Artem Kharchenko

National Technical University «Kharkiv Polytechnic Institute»
e-mail: zakovorotniy@kpi.kharkov.ua
Received November 2018

Summary. The paper developed a complex mathematical model of the rolling stock movement that takes into account the parallel operation of two real traction asynchronous engines of the first traction railway carriage and one equivalent engine of the second traction railway carriage of the diesel train in all modes of work, as well as the main types of oscillations of the train wagons, the forces distribution of interaction between them during the movement, as well as longitudinal and transverse elastic couplings of the wheel pair with the carriage of the car. In the article, the adequacy of the processes, resulting from three-dimensional modeling, processes occurring in the real diesel train DEL-02. On the complex mathematical model, were carried out tests on the effect of the main types of wagon oscillations to the motion and energy expenditure of a diesel train.
Key words: complex mathematical model, asynchronous engine, fluctuation of train carriages, diesel train.

INTRODUCTION

At present, a lot of mathematical models of DEL-02 diesel trains are known which make it possible to investigate and optimize the different modes of the train movement, the work of its traction asynchronous electric drives, as well as individual units and assemblies [1-6]. Most of the research is done on models that contain one or two equivalent traction engines and are described by systems of ordinary nonlinear differential equations that allow describing with sufficient accuracy the electromagnetic processes in the engines, the acceleration modes, the train motions over the distances with the known path profile and braking. In this case, the three-component rolling stock is represented as a single-mass or three-mass system [7, 8]. In the latter case, it is possible to investigate the forces acting between the wagons, as well as the longitudinal oscillatory processes between the wagons that can arise in the composition and lead to additional energy expenditure during the movement of the diesel train, and to the possible uncomfortable sensations for passengers. However, in the process of moving along the railway track, the rolling stock experiences more complex oscillatory movements, which are caused by uneven methods, the presence of gaps on the rail joints, the conicity of the rolling surface of wheel sets, and the presence of unevenness on this surface, the type of spring suspension and other factors. The mechanical vibration dampeners existing in the railway wagons, reducing the influence of dynamic influences and, the more so, to provide the smooth movement of the rolling stock, but these effects still lead to the fact that the carriages of the rolling stock are in an oscillatory state. In this case, each type of oscillation can occur separately or together with other types of oscillation. Based on this, a complex mathematical model, should take into account not only longitudinal oscillations, as well as other types of vibrations during the movement (transverse drift, wobble), and also take into account the longitudinal and transverse elastic bonds of wheel pairs of the railway wagons. In addition, the complex mathematical model should include variables that characterize both individual traction electric drives, as well as the parameters of the train itself, its components and force arising from the interaction of railway wagons during its movement. This, in its turn, makes it possible to parallel study of forces on a complex mathematical model, which exist between wagons, the causes of oscillations, their nature and mutual influence, as well as the influence of mechanical vibrations on electromagnetic processes in traction engines, determine the laws of optimal control, when solving the problems of costs optimization by rolling stock movement as well as to determine the conditions for the steady and safe movement of the train along railway tracks with irregularities. In addition, the complex mathematical model makes it possible to carry out the studies described above not only at the speeds of rolling stock that are currently accepted by the Ukrainian railways (up to 100 - 120 km/h), but also at speeds characteristic of high-speed traffic of trains, because constructively diesel train DEL-02 can reach speeds of up to 140 km/h. This makes it possible to clarify the results of studies of the parallel operation of traction motors, slipping processes, and wagon oscillations for increased train speeds. The latter is especially relevant in connection with the fact that the wagon fluctuations directly depend, on the one hand, from the speed of rolling stock movement, because with the increase in the route speeds of train traffic along the railway lines, the amplitude and frequency of oscillations can increase, and on the other hand, the quality of the railroad track, and the presence of unevenness on the surface of the railway track can results in the appearance of transverse oscillations.

PURPOSE AND TASKS OF RESEARCH

The aim of the article is to develop a complex mathematical model of the rolling stock movement that takes into account the parallel work of two real traction induction motors, the first traction wagon with engine and one equivalent engine of the second traction wagon with engine of a diesel train, in all modes of their work, as well as the main types of oscillations of the train wagons and the distribution of forces of interaction between them during the movement and transverse oscillations and wobble of wheel sets.

COMPLEX MATHEMATICAL MODEL OF DIESEL TRAIN MOVEMENT

For a complete and accurate description of the processes occurring on the diesel train during its movement, the mathematical model of the object should include variables that characterize not only the main types of wagon oscillations, but also individual traction electric drives, as well as the parameters of the train itself, its components and forces arising from the interaction of train cars in the movement process [9, 10]. In this connection, a complex mathematical model for the motion of a diesel train has been developed. This model simulates a rolling stock of three railway wagons (two motor railway wagons and one non-motorized) and takes into account the main types of oscillations of train wagons, the distribution of interaction forces between them and the possibility of slippage during the movement of the train. At the same time, the model uses real traction motors in the first railway wagon with engine and an equivalent traction engine in the second railway wagon wit engine. In the mathematical model of diesel train movement, two identical idealized models of traction asynchronous motors are used, and two models differing in parameters [9, 10]. This is due to the fact that on the real diesel train in each of the two engine-wagons and the mechanical parts of the two engines are not exactly the same, because in their production it is impossible to exactly observe the symmetry of the stator and rotor windings, the smoothness of the air gaps, the sinusoidal distribution of the magnetic streams and scattering fluxes, as well as losses in steel, from which engine components are manufactured.

The complex mathematical model can be represented by the following system of twenty-five ordinary nonlinear differential equations of the first order with six controls, and equations (2) - (5) can be written both through the flux linkages and through the currents of the motors:

$$\frac{dS}{dt} = k_1 V_1; \qquad (1)$$

$$\begin{aligned} \frac{d\Psi_{\alpha 1}^q}{dt} &= b_1^q U_\alpha^q - a_s^q \Psi_{\alpha 1}^q + a_s^q k_r^q \Psi_{\alpha 2}^q = \\ &= U_\alpha^q - r_1^q i_{\alpha 1}^q,\ q = \overline{1,3}; \end{aligned} \qquad (2)$$

$$\begin{aligned} \frac{d\Psi_{\beta 1}^q}{dt} &= b_2^q U_\beta^q - a_s^q \Psi_{\beta 1}^q + a_s^q k_r^q \Psi_{\beta 2}^q = \\ &= U_\beta^q - r_1^q i_{\beta 1}^q,\ q = \overline{1,3}; \end{aligned} \qquad (3)$$

$$\begin{aligned} \frac{d\Psi_{\alpha 2}^q}{dt} &= -a_r^q \Psi_{\alpha 2}^q + a_r^q k_s^q \Psi_{\alpha 1}^q - \omega^q \Psi_{\beta 2}^q = \\ &= -r_2^q i_{\alpha 2}^q - \omega^q \Psi_{\beta 2}^q,\ q = \overline{1,3}; \end{aligned} \qquad (4)$$

$$\frac{d\Psi^q_{\beta 2}}{dt} = -a^q_r\Psi^q_{\beta 2} + a^q_r k^q_s \Psi^q_{\beta 1} - \omega^q \Psi^q_{\alpha 2} = = -r^q_2 i^q_{\beta 2} - \omega^q \Psi^q_{\alpha 2},\ q = \overline{1,3}; \tag{5}$$

$$\frac{d\omega^q}{dt} = \frac{p}{J^q}\left(\frac{3}{2}p\frac{k^q_r}{\sigma^q L^q_s}\frac{i}{R^q}(\Psi^q_{\alpha 2}\Psi^q_{\beta 1} - \Psi^q_{\alpha 1}\Psi^q_{\beta 2}) - \right. - a_0 - a_1\omega^q - a_2(\omega^q)^2 - i(S) - \omega_r(S) + \left. + \eta^q_\delta(t)\right),\ q = \overline{1,3}; \tag{6}$$

$$\frac{dV_1}{dt} = \frac{1}{m_M}\left(\sum_{q=1}^{2}\frac{3}{2}p\frac{k^q_r}{\sigma^q L^q_s}\frac{i}{R^q}\cdot \right. \cdot \left.(\Psi^q_{\alpha 2}\Psi^q_{\beta 1} - \Psi^q_{\alpha 1}\Psi^q_{\beta 2}) - F_{12} - F_{c1}\right); \tag{7}$$

$$\frac{dV_3}{dt} = \frac{1}{m_M}\left(\frac{3}{2}p\frac{k^3_r}{\sigma^3 L^3_s}\frac{i}{R^3}\cdot \right. \cdot \left.(\Psi^3_{\alpha 2}\Psi^3_{\beta 1} - \Psi^3_{\alpha 1}\Psi^3_{\beta 2}) + F_{23} - F_{c3}\right); \tag{8}$$

$$\frac{dV_2}{dt} = \frac{1}{m_T}(F_{12} - F_{23} - F_{c2}); \tag{9}$$

$$\frac{dF_{12}}{dt} = C_{12}(V_1 - V_2); \tag{10}$$

$$\frac{dF_{23}}{dt} = C_{23}(V_2 - V_3); \tag{11}$$

$$\frac{dQ}{dt} = g_1;\ \frac{dg_1}{dt} = -\frac{2K}{m_{wp}}\cdot\frac{1}{V_2}g_1 - -\frac{2K}{m_{wp}}\varphi - \frac{2C_y}{m_{wp}}Q; \tag{12}$$

$$\frac{d\varphi}{dt} = g_2;\ \frac{dg_2}{dt} = -\frac{2Kl^2}{J_{wp}}\cdot\frac{1}{V_2}g_2 + +\frac{2Klh_c}{J_{wp}R^4}Q - \frac{2C_x l^2}{J_{wp}}\varphi, \tag{13}$$

where S is the distance that the diesel train passes and is counted from the start of the railway path; t is time; k_1, b^q_1, b^q_2, $a^q_s = \frac{1}{\sigma^q T^q_s}$, $k^q_r = \frac{L^q_m}{L^q_r}$, $a^q_r = \frac{1}{\sigma^q T^q_r}$, $k^q_s = \frac{L^q_m}{L^q_s}$, $\sigma^q = 1 - k^q_r k^q_s$, $T^q_s = \frac{L^q_s}{r^q_1}$, $T^q_r = \frac{L^q_r}{r^q_2}$, L^q_r, L^q_m, L^q_s, r^q_1, r^q_2 ($q = \overline{1,3}$) are constant coefficients that take into account the variants of the two real processes of the first railway wagon with engine and one equivalent drive unit of the second railway wagon with engine; q is number of engines; V_1, V_2, V_3 are speeds of movement, respectively, of the first, second and third railway wagons of the diesel train (Fig. 1); $\Psi^q_{\alpha 1}$, $\Psi^q_{\beta 1}$ ($q = \overline{1,3}$) are the projections on the α and β axes of the stator flux linking, respectively, of the two real engines of the first railway wagon with engine and one equivalent drive of the second railway wagon with engine; U^q_α, U^q_β ($q = \overline{1,3}$) are projections on the α and β axes of the stator windings of the two real motors of the first railway wagon with engine and one equivalent drive unit of the second wagon with engine, respectively; $\Psi^q_{\alpha 2}$, $\Psi^q_{\beta 2}$ ($q = \overline{1,3}$) are projections on the axis α and β of the flux linkages of the rotor, respectively, of the two real engines of the first wagon with engine and one equivalent drive unit of the second wagon with engine; ω^q ($q = \overline{1,3}$) are angular rotational speeds of the rotors, respectively, of two real engines of the first wagon with engine and an equivalent second wagon with engine; p is the number of pole pairs of the stator of each motor; J^q ($q = \overline{1,3}$) is the moment of inertia of the engine and the mechanism, connected to the shaft, respectively, of the two real engines of the first railway wagons with engines and one equivalent drive unit of the second railway wagon with engines; i is reducer gear ratio; R^q ($q = \overline{1,3}$) is wheel radii correspondingly of the motor pair of the first wagon with engine with two real engines and one wheel pair of the second wagon with engine with one equivalent drive; a_0, a_1, a_2 are constant coefficients, are constant coefficients which characterize the load torque; $i(S)$ is function of resistance from the slopes of the path profile; $\omega_r(S)$ is resistance function from path profile curves; $\eta^q_\delta(t)$, $q = 1, 2$ is random function for simulate the possibility of slippage, $\eta^3_\delta(t) = 0$; m_M, m_T are the weights of the wagon with engine and trailed railway wagons respectively; F_{12}, F_{23} are forces acting between the first and second the second and third wagons of the train respectively; F_{c1}, F_{c2}, F_{c3} are forces of resistance to movement of the first, second and third railway wagons respectively; C_{12}, C_{23} are elasticity coefficients between the first and second, and the second and third railway wagons; Q is the amount of lateral deviation (drift) of the wheel pair of the second railway wagon; g_1, g_2 are intermediate variables; K is creep coefficient; m_{wp} is mass of the wheel pair of the second railway wagon; φ is angle of waggling of the wheel pair of the second railway wagon; C_y, C_x are rigidities of transverse and longitudinal bonds respectively; l is half distance between wheels on the wheel pair of the second railway wagon; J_{wp} is moment of inertia of the wheel pair of the second railway wagon; h_c is conicity of the wheels of the second railway wagon; R^4 is wheel radius of the second railway wagon.

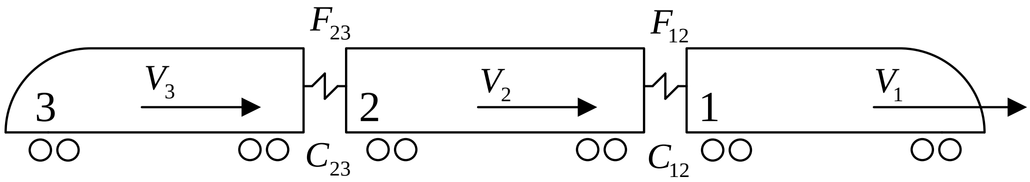

Fig.1. The speeds of movement of diesel train railway wagons, the coefficients of elasticity and the forces acting between the railway wagons

Model (1) - (13) includes: equation (1), which describes the distance that the rolling stock passes over the time interval of control; equations (2) - (6), describe the processes taking place in two real drives of the first railway wagon and the equivalent drive of the second railway wagon, while (2) - (5) simulate the main electromagnetic processes (via flux linkages or currents), and equations (6) – mechanical part of three traction asynchronous electric drives; equations (7) - (9), describe the speeds of three carriages of rolling stock; equations (10), (11) simulate the forces that act between the wagons of the train; (12), (13), describe the level of lateral deviation and the angle of waggling of the railway wagons wheel pair (Fig. 2).

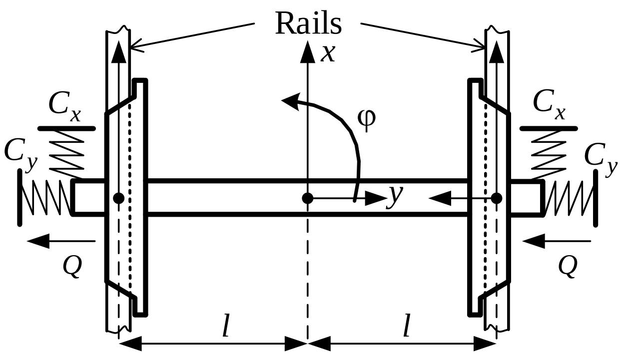

Fig. 2. Forces acting on the wheel pair, which is connected with the carriage by elastic bonds

Comparison of simulation results on the developed model with the results of experimental studies on a diesel train confirmed the adequacy of the obtained model. The complex mathematical model (1) - (13), unlike existing models with one equivalent traction drive, allows to simultaneously study electromagnetic and electromechanical processes of three diesel train engines simultaneously, simulate skidding of wheel pairs on any of the two engines of the first railway wagon with engine, and also determine the distance that the rolling stock passes during the control time. In addition, in contrast to models that take into account only the longitudinal oscillations of the train wagons [7, 8], model (1) - (13) also takes into account the oscillations associated with the lateral deviation of the diesel train wagons (transverse oscillations), as well as influence of wagons rolling stock wobble in the process of its movement over the railway path for the process of train engine work.

Using the model (1) - (13), several types of processes can be modeled:

1) acceleration of diesel trains, which, depending on the acceleration mode can last up to 100 - 160 seconds;

2) the oscillations of the diesel train wagons, the period of the oscillation, depends from the loading of the railway wagons and lasts to 80 seconds;

3) electromagnetic processes in the electric drive, where the frequency of the supply voltage can vary from the fraction of the hertz to 200 Hz;

4) transverse oscillations of wheel pairs and their wagging, where the oscillation frequency is several hertz.

Since the time constants of different processes differ by orders of magnitude, the initial model does not make sense to use for the study of any processes, since this substantially increases the expenditure of computer time. The need for this model arose from the experimental trips of a diesel train at speeds exceeding 130 to 135 km/h, when there are quite strong transverse oscillations that could not be explained without simulating the movement of the wheel pair (Fig. 2) with the aid of relations (12) and (13).

Simulation (Fig. 3 - Fig. 6) was carried out with real parameters of the wheel pair of diesel train DEL-02. In Fig. 3 shows the curves of the lateral deviation Q and the angle of wagging φ of the wheelset of the wagon of the rolling stock during the passage of irregularities with the value of the initial deviation Q_{in} = 0,003 m at three different speeds of the diesel train. In this case, the curves Q_1, Q_2, Q_3 (Fig. 3, *a*) show the values of lateral deviation, and the curves φ_1, φ_2, φ_3 (Fig. 3, *b*) the angle of waggling of the wagon wheel pair at the speeds of the diesel train, such as 100 km/h, 120 km/h, 140 km/h, respectively.

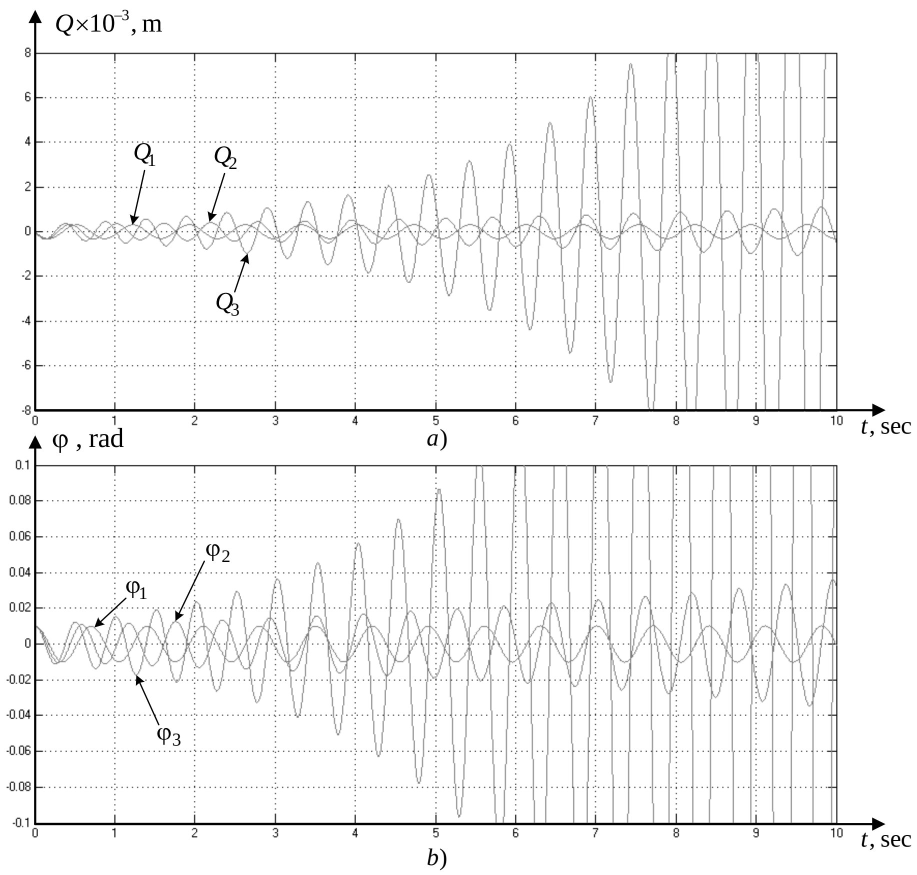

Fig. 3. Graphs of lateral deviation and the angle of wagging of the wheeled pair of the wagon of rolling stock

It can be seen from the graphs in Figs 3, *a* and *b* that with increasing speed of the diesel train along sections of the railway track with irregularities, the frequency of the oscillations of the lateral ratio of the wheel pair of the railway wagon increases, as well as the rate of increase in the amplitude of the oscillations. In this case, fluctuations wagging of wheel pairs of the railway wagon have a similar character. Experiments on the models clearly explain the reasons for the appearance of strong transverse oscillations of railway wagons at speeds of the elements above 130 km/h.

In Fig. 4 shows the lateral deviation graphs (Fig. 4, *a*) and the wagging angle (Fig. 4, *b*) of the wheeled wagon of the rolling stock during the passage of the unevenness with the value of the initial displacement Q_{in} = 0,003 m at a speed $V \approx$ 120 km/h for different values of the creep coefficient (K_1 = 10000 kN, K_2 = 15000 kN, K_3 = 20000 kN). It can be seen from the graphs in Fig. 4, *a* and Fig. 4, *b* that with an increase in the coefficient of creep the frequency of oscillation of the wheel pair of the railway wagon does not change, and the amplitude of the oscillations of the lateral ratio and the angle of wagering of the wheel pair decreases.

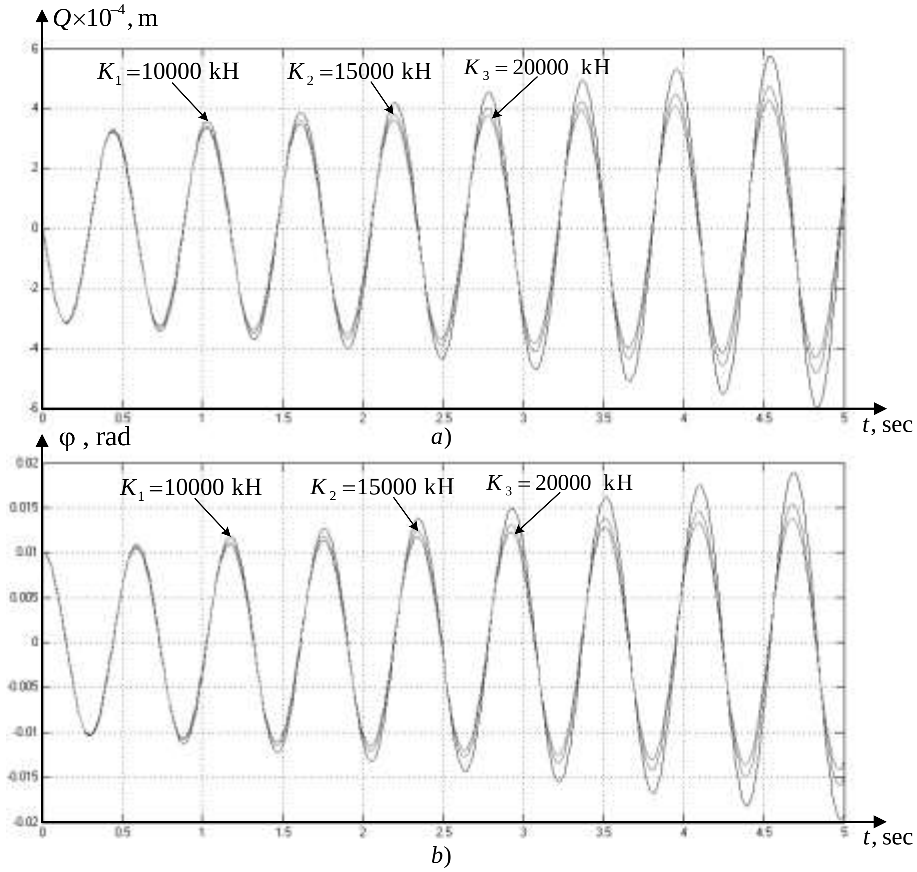

Fig. 4. Graphs of lateral deviation and the angle of wagging wheeled wagon rolling stock in the case of a change in the coefficient of creep

In Fig. 5 shows the lateral deviation graphs (Fig. 5, *a*) and the wagging angle (Fig. 5, *b*) of a wheeled wagon of a rolling stock in the process of passing an roughness with the value of the initial displacement $Q_{in} = 0{,}003$ m at speed $V \approx 120$ km/h for different values of the taper of a pair of wheels ($h_c = 0{,}02$; $h_c = 0{,}05$; $h_c = 0{,}08$). From the graphs in Fig. 5, *a* and Fig. 5, *b* can be seen that with increasing taper rolling surface, wheelset increases the frequency and amplitude of the oscillations and the lateral deflection of the wheelset yaw angle of diesel trains wagons.

In Fig. 6 shows the graphs of lateral deviation and the angle of wobble of the wheeled wagon during the acceleration of the diesel train to speed $V = 120$ km/h on an uneven section of the railway track with the next roughness: in a period of time $t = [0 - 20]$ sec – the initial value of offset $Q_{in} = 0{,}005$ m; in a period of time $t = [20 - 60]$ sec – the initial value of offset $Q_{in} = 0{,}003$ m; in a period of time $t = [60 - 100]$ sec – the initial value of offset $Q_{in} = -0{,}002$ m; in a period of time $t = [100 - 120]$ sec – the initial value of offset $Q_{in} = 0{,}001$ m.

From the graphs in Fig. 6 it becomes obvious that as the speed of the rolling stock increases during acceleration along the uneven part of the railway track, the frequency and amplitude of the longitudinal oscillations and the angle of wagging of the wheel pair of the diesel train wagon tends to increase, which leads to uncomfortable sensations (swaying) of the train passengers, even at the small speed of the rolling stock along the sections of the road with small irregularities. In this regard, it is necessary to take into account the lateral deviation and the angle of wagging of rolling stock wagons when synthesizing the optimal rules control the diesel train to ensure comfortable conditions for passengers during the movement of the train at high speeds.

In studies of diesel train work processes at speeds of up to 120 - 130 km/h, relations (12) and (13) it is advisable to exclude from the model.

In investigating of acceleration processes, movement rolling stock processes at constant speed, on coasting and braking can be used a system of equations (1) - (11).

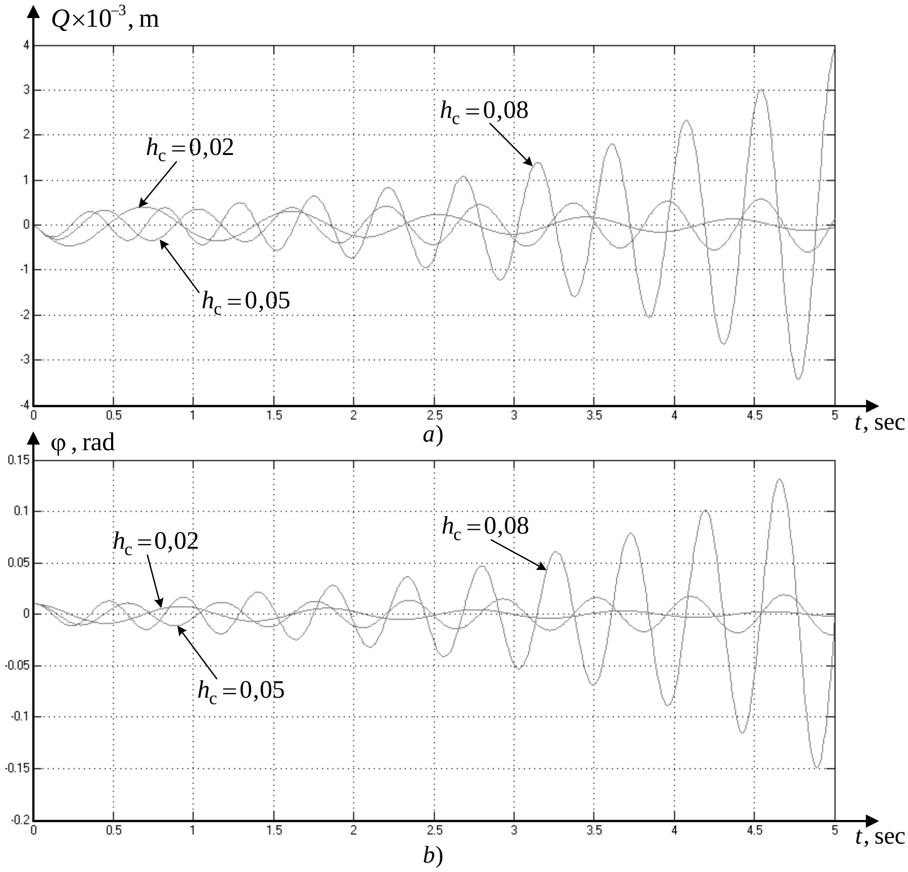

Fig. 5. Graphs of lateral deviation and the angle of waggling of the wheelset of the wagon of rolling stock for different values of taper

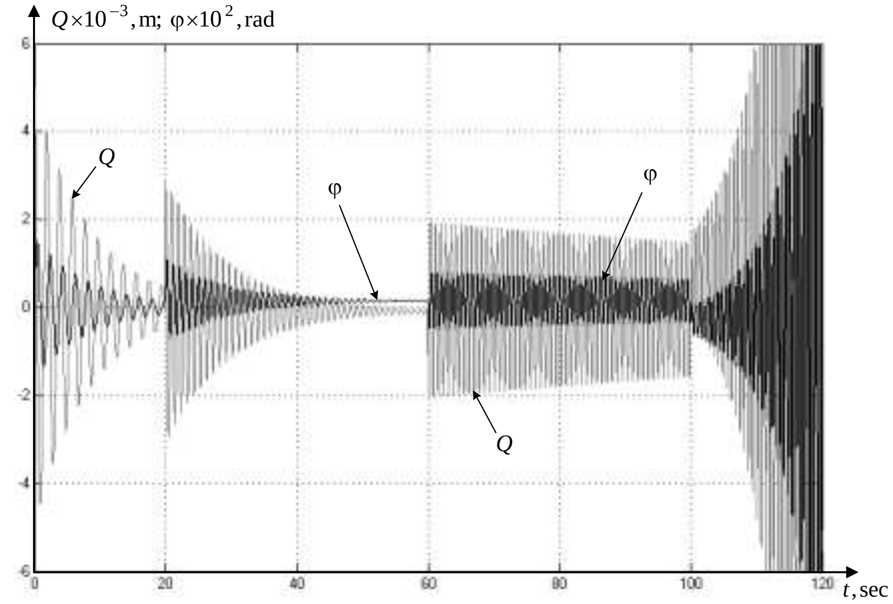

Fig. 6. Graphs of lateral deviation and wobble of the wheel pair of the diesel train wagon during its acceleration on an uneven section of the track

In Fig. 7 shows the graphs of the time changes of the first, second and third railway wagons of diesel train, obtained with the help of the developed complex mathematical model (1) - (13) (curves V_1, V_2, V_3), acceleration of the first train railway wagon (curve a), the traversed path (curve S_1), forces, acting between the first and second (curve F_{12}), and the second and third train railway wagons (curve F_{23}) as it moves between the two stations, as well as the position of the traction (curve N_{cm}) and the brake (curve N_{tcm}) controllers of the train machinist. Also, Fig. 7 shows the graphs of the processes, obtained with the use of one (first) railway wagon with drive of the diesel train, operating at 1 to 6 positions of the driver's traction controller (curve N_{tcm}). In addition, in Fig. 7 also shows graphs of the variation the speed of train motion in time (curve V_t) and the path, traversed by the train from the start of the railway track section (curve S_2) obtained on the real object by means an onboard diesel train information-measurement system of DEL-02, during its movement over the smooth section of railway track S = 3 km during the time t = 5 min.

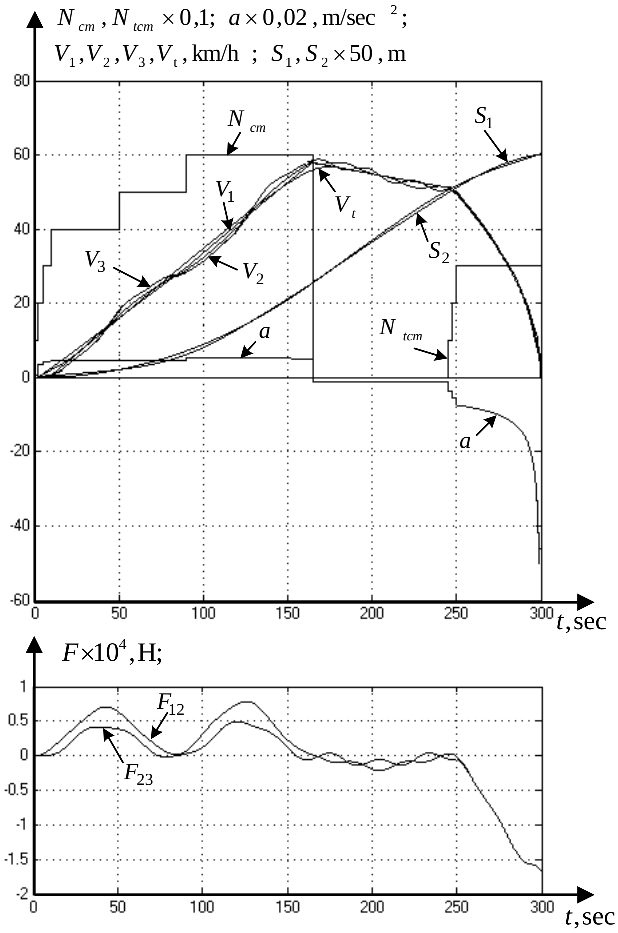

Fig. 7. Graphs of the main processes of motion, obtained on the complex mathematical model (1) - (11) and the real diesel train DEL-02

From Fig. 7 that the graphs of the speed and the path, traversed by the rolling stock, obtained with the help of the complex mathematical model (1) - (11) and on the real diesel train DEL-02, practically coincide. And also, the value of the forces acting between the first and second (Fig. 7, the curve F_{12}), and the second and third railway wagons of the train (Fig. 7, curve F_{23}) coincides with the same forces that are modeled in the works [7, 8]. All this testifies to the adequacy of the complex mathematical model (1) - (11) to the real object of control, which is a diesel train DEL-02.

In the case when the processes of skidding and longitudinal oscillations of wagons have already been studied, when only motion modeling operations of diesel train along a section of the railway track are needed, from model (1) - (13) it is necessary to exclude only the first six equations, with one equivalent electric motor.

A lot of experiments that were carried out on the complex mathematical model (1) - (13) and the real diesel train DEL-02, confirmed the adequacy of the model to the control object under consideration. In this regard, the model (1) - (13) can be used to study the dynamic processes of trains motion with traction asynchronous drives, check the optimal control rules for rolling stock.

INVESTIGATION OF THE DYNAMIC PROCESSES OF ROLLING STOCK MOTION ON A COMPLEX MATHEMATICAL MODEL

Consider using a complex mathematical model (1) - (13) example of mutual influence of longitudinal and transverse vibrations while driving railway wagons of diesel train on the route between two stations, the distance between which is S = 3 km, in a period of time t = 5min on an even section of the railway track, taking into account the unevenness of the railway track and the current limits on the maximum acceleration value $(-1 \div -0{,}7\ \mathrm{m/sec^2} \le a \le 0{,}7 \div 1\ \mathrm{m/sec^2})$, related to the comfort of traveling passengers in the modes of acceleration and braking.

In Fig. 8 shows the results of modeling, on a complex mathematical model (1) - (13), the motion of a diesel train on a flat section of a railway track with three irregularities on t = 50 sec, 150 sec and 250 sec with the value of the initial displacement of the railway wagon $Q_{in} = 0{,}03$ m.

In Fig. 8, as represented the graphics positions of the traction in time change (N_{cm}) and brake (N_{tcm}) controllers of the machinist, instantaneous speeds of the first, second and third railway wagons of the diesel train (V_1, V_2, V_3), the way that was passed (S), as well as energy (E), that consumes diesel train while moving between two stations. In Fig. 8, *b* shows the variation of the distance between the railway wagons of the train, and in this case the curves dS_{12} and dS_{23} show the change in the distance between the first and second, and second and third train wagons, respectively. In Fig. 8, *b* the presented graphs of the variation in time of forces acting between the first and second (curve F_{12}), and second and third railway wagons (curve F_{23}) when moving a diesel train between two stations along a section of the road with irregularities.

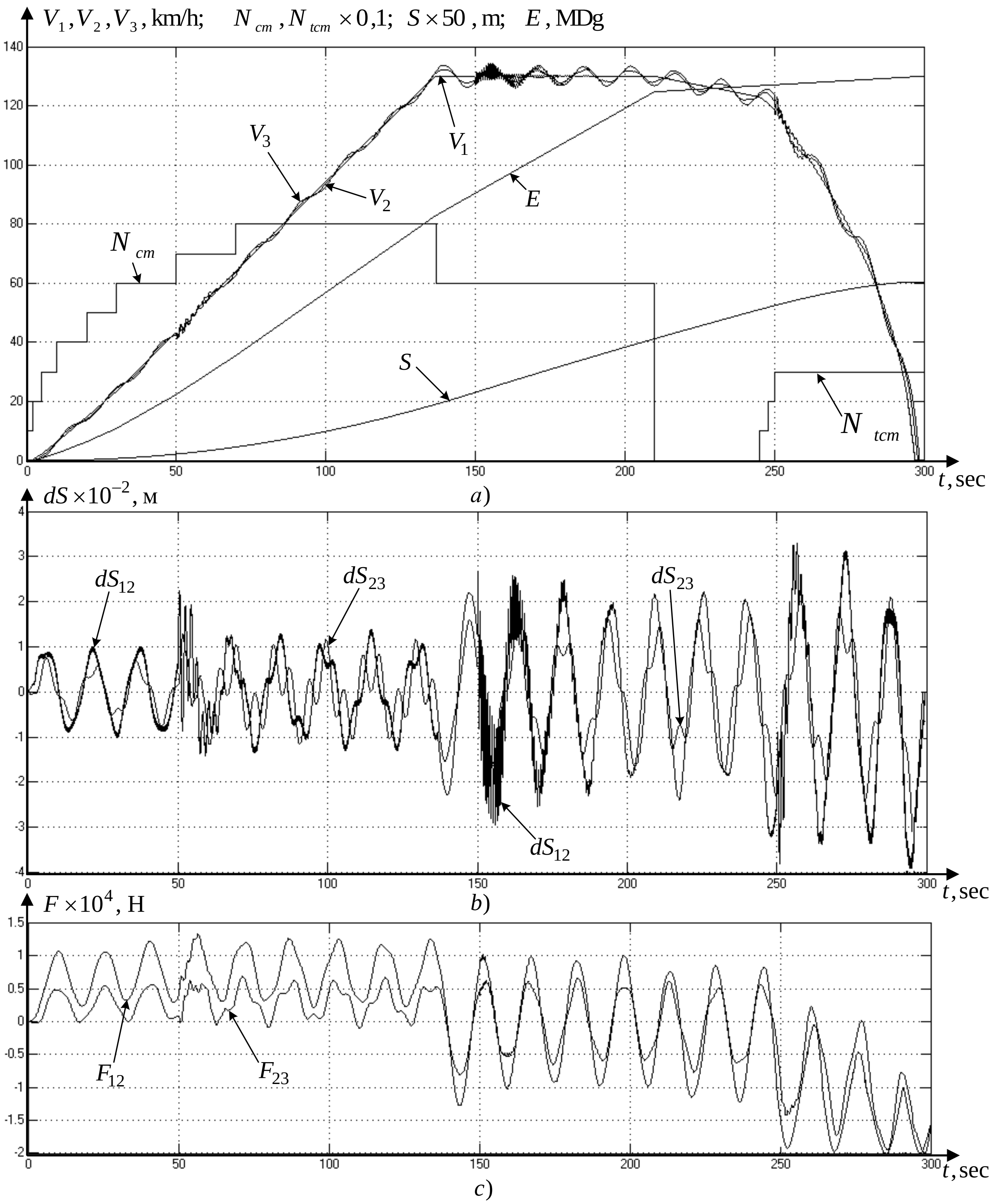

Fig. 8. Results of modeling the diesel train motion on a complex model (1) - (13)

In Fig. 9, curves *Q* and φ, show, respectively, the lateral deviation and the angle of wagging of the second railway wagon of the train when it passes through irregularities along the above-described section of railway path.

From the graphs in Fig. 8 it can be seen that during the passage of the diesel-train sections of the road with irregularities, the lateral deflection *Q* and the wobbling angle φ of the second train wagon, shown in Fig. 9, affects the longitudinal oscillations of all the railway wagons of the train, which leads to their jerking and changing the distance between the first and second, and also the second and third railway wagons of the train. In addition, lateral deviation and wagging of the second railway wagon affects the forces acting between the railway wagons, which manifests itself in the form of insignificant oscillations of forces acting between the first and second, and also the second and third railway wagons of the rolling stock (Fig. 9, time intervals [50, 75] sec, [150, 175] sec, and [250, 275] seconds).

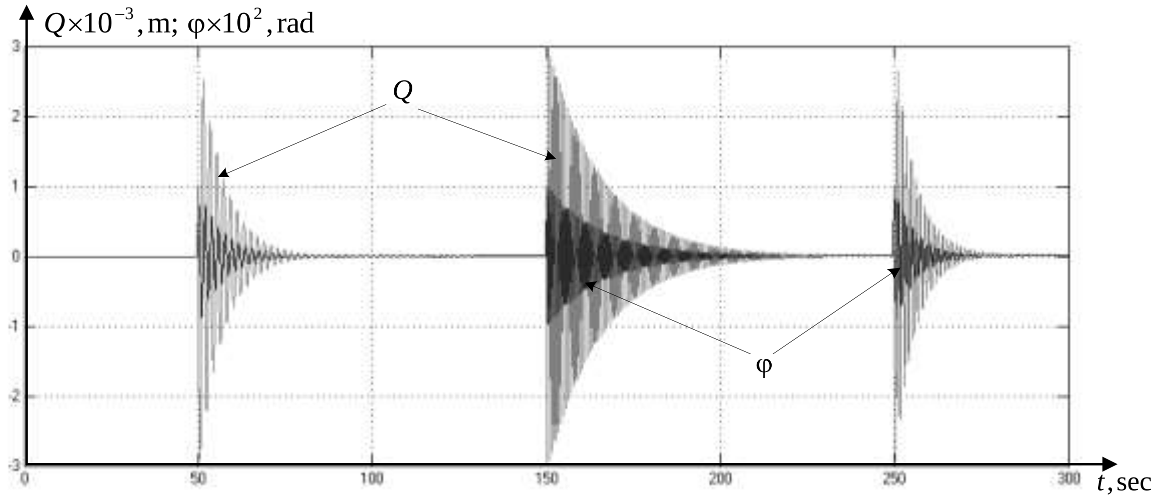

Fig. 9. Transverse vibrations and the angle of wagging of the second railway wagon when the diesel train is moving

CONCLUSIONS

The theory of traction rolling stock modeling has been further improved by developing a complex mathematical model for the motion of diesel trains, which is in contrast to existing models allows you to explore a wide range of dynamic operating modes: longitudinal oscillations of wagons, lateral deviations and angles of waggering of rolling stock cars, modes of acceleration, traction and braking of the train, taking into account skidding, as well as electromagnetic processes in electric motors, which made it possible to more accurately describe the processes, taking place in the control object.

REFERENCES

1. **Dmitrienko, V.D., and Zakovorotniy, A.Y**. *Modeling and optimization of traffic control processes of the diesel trains [monograph]*, Kharkiv: Publishing center «HTMT», 2013. (In Russian).
2. **Noskov V.I., and Dmitrienko V.D., and Zapolovsky N.I., and Leonov S.Yu.** *Modeling and optimization of locomotive control and monitoring systems*. Kharkiv: Transport of Ukraine, 2003. (In Russian).
3. **Volkov, A.V., and Kosenko, I.A.** Asynchronous motor drive based on self-excited current inverter with switched-off thyristors and provided with predicting relay and vector regulation of stator current, *Published in Elektrotekhnika*, 2008, no. 10, p. 6–17.
4. **Sandler, A.S., and Sarbatov, R.S.** *Automatic frequency control of asynchronous motors*, Moscow: Energiya, 1974. (In Russian).
5. **Orlovskiy, I.A.** Determination of the parameters of nonlinear regulators in control systems using artificial intelligence

methods, *Technical electrodynamics*, 2006, vol. 7, pp. 57–62. (In Russian).

6. **Orlovskiy, I.A.** Evaluation of the state vector of an asynchronous motor by an artificial neural network, *Automation of processes and control, Bulletin of SevNTU*, 2004, vol. 58, pp. 150 – 160. (In Russian).
7. **Orlovskiy, I.A., and Kuleshov, A.N.** The account of elastic connections and the distributed loading at a vector control of an asynchronous traction drive of a diesel train, *Science and transport progress. Bulletin of Dnepropetrovsk National University of Railway Transport*, 2007, vol. 19, pp. 209–213. (In Russian).
8. **Orlovskiy, I.A., and Golyanchuk, Yu.V.** Mathematical model on the recurrent neural network of the mechanics of the motion of diesel-train wagons, *Bulletin of the KPUU named after Mikhail Ostrogradsky. Series «Information Systems and Modeling»*, 2009, vol. 3 (56), no. 2, pp 116–119. (In Russian).
9. **Dmitrienko, V.D., and Zakovorotniy, A.Y.** Automation symbolic calculations in the process of transformation nonlinear models of objects to equivalent linear, *Transaction of Azerbaijan National Academy of Sciences, Series of Physical-Technical and Mathematical Sciences: Informatics and Control Problems*, 2014, vol. XXXIV, no. 6, pp. 130–139. (In Russian).
10. **Zakovorotniy, A.Y.** Expanding the possibilities of geometric control theory by automating analytical transformations in the package Matlab, *Bulletin of NTUU «KPI»*, 2016, vol. 64, pp. 76–83. (In Russian).

КОМПЛЕКСНАЯ МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ДВИЖЕНИЯ ТЯГОВОГО ПОДВИЖНОГО СОСТАВА

Валерий Дмитриенко, Александр Заковоротный, Валентин Носков, Николай Мезенцев, Дмитрий Главчев, Артем Харченко

Аннотация. Разработана комплексная математическая модель движения состава, которая учитывает параллельную работу двух реальных тяговых асинхронных двигателей первого обмотореного вагона и одного эквивалентного двигателя второго обмотореного вагона дизель-поезда во всех режимах их работы, а также основные виды колебаний вагонов поезда и распределение сил взаимодействия между ними во время движения и продольные и поперечные упругие связи колесной пары с тележкой вагона. Приведена проверка адекватности процессов, полученных моделированием, процессам, протекающим в реальном дизель-поезде ДЭЛ-02. На комплексной математической модели проведены исследования по влиянию основных видов колебаний вагонов на процессы движения и расходы энергии дизель-поезда.

Ключевые слова: комплексная математическая модель, асинхронный двигатель, колебание вагонов поезда, дизель-поезд.